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GAS FILLED HALLOW CORE FIBER LASERS BASED ON POPULATION INVERSION

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Final Report

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Hollow-core Optical Fiber Gas LASer (HOFGLAS) have been created, and explored in pulsed mode with C2H2 and HCN gas inside the hollow core of a kagome structured photonic crystal fiber, and near- ideal efficiencies were realized for wavelengths near 1.5 µm (pump, 1 ns-pulses) and 3 µm (lasing). Improved fiber loss is realized near 3 µm to <1 dB/m. In addition, a pulsed CO2 waveguide (silver coated hollow capillary) laser demonstrated efficient lasing at ~4.3 • m. Toward cw lasing, the fluorescence from a hollow fiber filled with molecular iodine (I2) and pumped at ~ 532 nm was studied. Toward improved fiber transmission measurements, novel thulium/holmium fiber laser near 2 microns were created.

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A. Project Summary/Abstract

GAS-FILLED HOLLOW CORE FIBER LASERS BASED ON POPULATION INVERSION
Final Performance Report
Submitted to: Dr. Howard Schlossberg
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Project Summary/Abstract

Abstract (<200 words)

We have created a new class of lasers known as Hollow-core Optical Fiber Gas LASer (HOFGLAS) combining the advantages of fiber lasers with those of gas lasers. Pulsed HOFGLAS has been studied with C_2H_2 and HCN gas inside the hollow core of a kagome structured photonic crystal fiber, and near- ideal efficiencies were realized. The gases are optically pumped near 1.5 μm using 1 ns-pulses and yield laser emissions near 3 μm. Furthermore, we have improved fiber loss near 3 μm to below the dB/m-levels. In addition, we have demonstrated a CO_2 waveguide (silver coated hollow capillary) laser lasing at ~4.3 μm when pumped at ~2.0 μm with 5-nanosecond pulses, and demonstrated a slope efficiency in terms of absorbed power of ~22%. We have explored the feasibility of cw lasing from a hollow fiber filled with molecular iodine (I_2) when pumped at ~ 532 nm, and have spectrally resolved the intensity dependence of fluorescence from a 10-cm photonic crystal fiber of ~80-μm diameter filled with I_2. In an effort to achieve near-IR sources for testing fiber transmission, we have demonstrated a novel thulium/holmium fiber laser near 2 microns.

Abstract (short):

Hollow-core Optical Fiber Gas LASer (HOFGLAS) have been created, and explored in pulsed mode with C_2H_2 and HCN gas inside the hollow core of a kagome structured photonic crystal fiber, and near- ideal efficiencies were realized for wavelengths near 1.5 μm (pump, 1 ns-pulses) and 3 μm (lasing). Improved fiber loss is realized near 3 μm to <1 dB/m. In addition, a pulsed CO_2 waveguide (silver coated hollow capillary) laser demonstrated efficient lasing at ~4.3 μm. Toward cw lasing, the fluorescence from a hollow fiber filled with molecular iodine (I_2) and pumped at ~ 532 nm was studied. Toward improved fiber transmission measurements, novel thulium/holmium fiber laser near 2 microns were created.

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C. People involved with this research grant:

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Chenchen Mao, University of New Mexico, Ph.D. candidate, now at University of Colorado Boulder

D. Archival publications (published) during reporting period:

1. "All-fiber passively mode-locked thulium/holmium laser with two center wavelengths", ◦Kadel, Rajesh; Washburn, Brian R, ◦Applied Optics, Vol. 51 Issue 27, pp.6465-6470 (2012). http://www.opticsinfobase.org/ao/abstract.cfm?URI=ao-51-27-6465
2. Andrew M. Jones, Ph.D. Thesis, Realizing a mid-infrared optically pumped molecular gas laser inside hollow-core photonic crystal fiber**,** Kansas State University (2012) http://jrm.phys.ksu.edu/theses.html
3. [Invited] "Hollow-core Optical Fiber Gas Lasers (HOFGLAS): a review", ◦Nampoothiri, A V Vasudevan; Jones, Andrew M; Fourcade-Dutin, C; Mao, Chenchen; Dadashzadeh, Neda; Baumgart, Bastian; Wang, Y Y; Alharbi, M; Bradley, T; Campbell, Neil; Benabid, F; Washburn, Brian R; Corwin, Kristan L; Rudolph, Wolfgang, Optical Materials Express, Vol. 2, Issue 7, pp. 948-961 (2012).

   http://www.opticsinfobase.org/ome/abstract.cfm?URI=ome-2-7-948
4. A. M. Jones, B. Baumgart, C. Mao, A. V. V. Nampoothiri, N. Campbell, C. F. Dutin, Y. Wang, F. Benabid, W. Rudolph, B. R. Washburn, and K. L. Corwin, "Efficient Mid-IR Lasing in Gas-Filled Hollow Waveguides," in CLEO: Science and Innovations, OSA Technical Digest (online), paper CM3N.2. (2012). http://www.opticsinfobase.org/abstract.cfm?URI=CLEO: S and I-2012-CM3N.2
5. A. M. Jones, C. Fourcade-Dutin, C. Mao, B. Baumgart, A. V. V. Nampoothiri, N. Campbell, Y. Wang, F. Benabid, W. Rudolph, B. R. Washburn and K. L. Corwin, "Characterization of mid-infrared emissions from C2H2, CO, CO2, and HCN-filled hollow fiber lasers", Photonics West January 2012, Proceedings of SPIE **8237,** 82373Y 10 pages, (2012). http://spiedigitallibrary.org/proceeding.aspx?articleid=1344580
6. A.M. Jones, A V V Nampoothiri, A. Ratanavis, T. Fiedler, N. V. Wheeler, F. Couny, R. Kadel, F. Benabid, B. R. Washburn, K. L. Corwin, and W. Rudolph, "Mid-infrared gas filled photonic crystal fiber laser based on population inversion," Optics Express, **19**, 2309-2316 (2011). http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-19-3-2309
7. A. M. Jones, A. V. V. Nampoothiri, A. Ratanavis, R. Kadel, N. V. Wheeler, F. Couny, F. Benabid, W. Rudolph, B. R. Washburn, and K. L. Corwin, "C^2H^2Gas Laser Inside Hollow-Core Photonic Crystal Fiber Based on Population Inversion," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (CD) paper CTuU1(2010). http://www.opticsinfobase.org/abstract.cfm?URI=CLEO-2010-CTuU1

D.1. Abstract of Ph.D. Thesis by Andrew Jones (item [2] above):

This research has focused on the development, demonstration, and characterization of a new type of laser based on optically-pumped gases contained within hollow optical fibers. These novel lasers are appealing for a variety of applications including frequency metrology in the mid-infrared, free-space communications and imaging, and defense applications. Furthermore, because of the hollow core fibers used, this technology may provide the means to surpass the theoretical limits of output power available from high power solid-core fiber laser systems. Gas-filled hollow-core fiber lasers based on population inversion from acetylene ($^{12}C_2H_2$) and hydrogen cyanide (HCN) gas contained within the core of a kagome-structured hollow-core photonic crystal fiber have now been demonstrated. The gases are optically pumped via first order rotational-vibrational overtones near 1.5 μm using 1-ns duration pulses from a home-built optical parametric amplifier. Narrow-band laser emission peaks in the 3-μm region corresponding to the $\Delta J = \pm 1$ dipole allowed rotational transitions between the pumped vibrational overtone modes and the fundamental C-H stretching modes have been observed in both molecules. High gain resulting from tight confinement of the pump and laser light together with the active gas permits these lasers to operate in a single pass configuration, without the use of any external resonator structure. Studies of the generated mid-infrared pulse energy, threshold energy, and slope efficiency as functions of the launched pump pulse energy and gas pressure have been performed and show an optimum condition where the maximum laser pulse energy is achieved for a given fiber length. The laser pulse shape and the laser-to-pump pulse delay have been observed to change with varying pump pulse energy and gas pressure, resulting from the necessary population inversion being created in the gases at a specific fiber length dependent on the launched pulse energy. Work is ongoing to demonstrate the first continuous wave version of the laser which may be used to produce a single coherent output from many mutually incoherent pump sources.

E. Summary of most important results

Here we describe the recent success we have had in demonstrating low pressure gas-filled fiber lasers. This grant began after the initial demonstration of the HOFGLAS, but has made possible the improvement in stability and quantitative assessment, the demonstration in HCN, CO and CO_2, and most particularly the improvement in fiber loss due to the fabrication of extremely low loss fibers spanning the near and mid–IR. We have published much of this work in an invited review paper [1], a Ph.D. thesis [2], and in additional journal and conference publications [3-8]. Furthermore, groundwork for additional progress in CW C_2H_2 lasers and I_2 lasers has been laid with this grant, and should see fruition soon. Here, we briefly summarize the work and highlight some interesting results, but refer the reader to publications for more detail.

E.1. C_2H_2 and HCN mid-IR gas-filled HCF laser based on population inversion

Our team demonstrated the first HOFGLAS in HCN and C_2H_2-filled hollow-core photonic crystal fibers [4, 9, 10]. The schematic diagram of the HOFGLAS is shown in Fig. 1. The observed C_2H_2 laser spectrum when pumped at 1.521 μm (R(7), v_1+v_3 transition) with 4 ns pulses is shown in Fig. 1 (a) together with a simplified energy level diagram. In principle, C_2H_2 can be pumped on any of the rotation-vibration transitions from the ground state to the v_1+v_3 vibrational state, and lasing occurs from the upper pumped rotational level. Typically, a pump wavelength is chosen close to the maximum absorption. The gain of such lasers is very high and its first demonstration was possible with a fiber exhibiting losses of 20 dB/m at the lasing wavelength and 0.75 dB/m losses for the pump (fiber A) [7, 9]. The laser spectrum contains two peaks corresponding to the R(7) and P(9) transitions [11] from the pumped state. Pump laser thresholds as low as 200 nJ were observed.

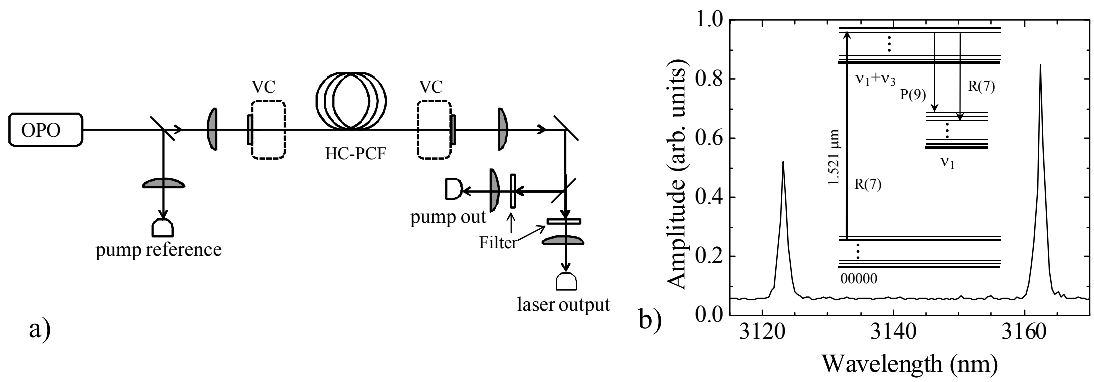

Fig. 1 a) Layout of the first gas filled hollow core fiber laser based on population inversion and b) recorded laser spectrum. A kagome HCF (HC-PCF) was used [12]. The inset shows the vibrational energy levels of C_2H_2 with the pump (optical parametric oscillator in the telecom C band) and observed lasing transitions. The fiber ends were housed in vacuum chambers (VC) in this proto-type. Fiber diameters are of the order of 20 – 40 μm.

More recently, pumping on the longer-wavelength P(13) transition, a wavelength that is more accessible for an Er-doped fiber amplifier, was demonstrated. Here the pump was a telecom signal laser that was amplified using an optical parametric amplifier (OPA). The P(13) absorption transition was excited with 1-ns pump pulses and the two lasing components shown in Fig. 1 (b) are shifted to 3114.6 nm and 3172.4 nm corresponding to the R(11) and P(13) transitions, respectively.

Furthermore, the funding provided by AFOSR led directly to the improved fabrication of fiber, and the realization of a highly efficient HOFGLAS laser. A kagome-structured fiber with hypocycloid core surround was fabricated (fiber B) as shown in Fig. 2 below, and gave improved guidance at the pump and lasing wavelengths.

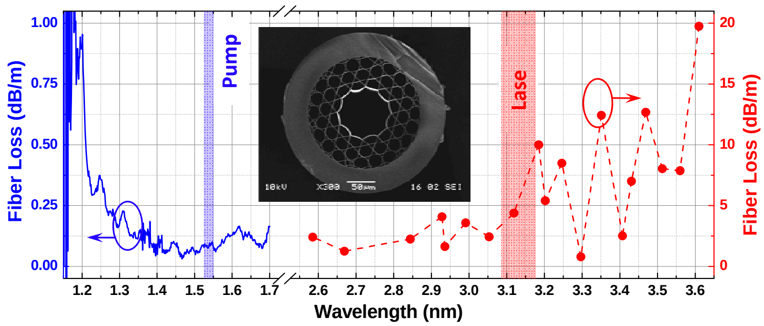

Fig. 2 Measured loss spectrum of the kagome-structured HCF used in the laser. The pump wavelengths are contained within the blue line near 1.53 μm, and the mid-IR laser wavelengths are contained within the red line near 3.1 μm. Inset: SEM image of the fiber end. The fiber is seen to have a pitch of 18.75 μm and a core diameter of 85 – 94 μm. Figure adapted from Ref. [6].

The HOFGLAS laser demonstrated in fiber B, shown in Fig. 2, produced efficient output and interesting saturation effects. Changing the length of the low loss kagome fiber from 146 cm to 45 cm does not have significant impact on the laser threshold or optical-to-optical efficiency. For the low-loss fiber a maximum efficiency of 27% was observed for a pressure of 2 torr, but at low output energies of 300 nJ. This is close to the theoretical limit of this system of 33% determined by simultaneous saturation of pump and lasing transitions, neglecting fiber loss. The highest energy pulses were observed at a pressure of 30 torr in a 46 cm long fiber; for 6 μJ of absorbed energy, 600 nJ were emitted in the mid-IR.

The molecules HCN and C_2H_2 have similar energy levels and similar HOFGLAS behavior is expected. Indeed, pumping the P(10), $2v_3$ transition [13] of HCN at 1541 nm using 1 ns pulses results in a spectrum similar to what is shown in Fig. 1 (b) for both fibers A and B. The two emission lines (now at 3091 nm and 3147 nm) also originate at the upper pump level and correspond to the R(8) and P(10) transition between the $J = 9$, $2v_3$ excited state and the $J = 8$ and $J = 10$, v_3 states[14].

To demonstrate additional laser schemes at other wavelengths, CO_2 and CO were explored using capillaries (Fig. 3). The capillaries served as test beds for HCFs whose cut-off wavelengths at that time were too short to support lasing at wavelengths > 3.5 μm. The lasers were pumped at about 2 μm using a nanosecond OPA.

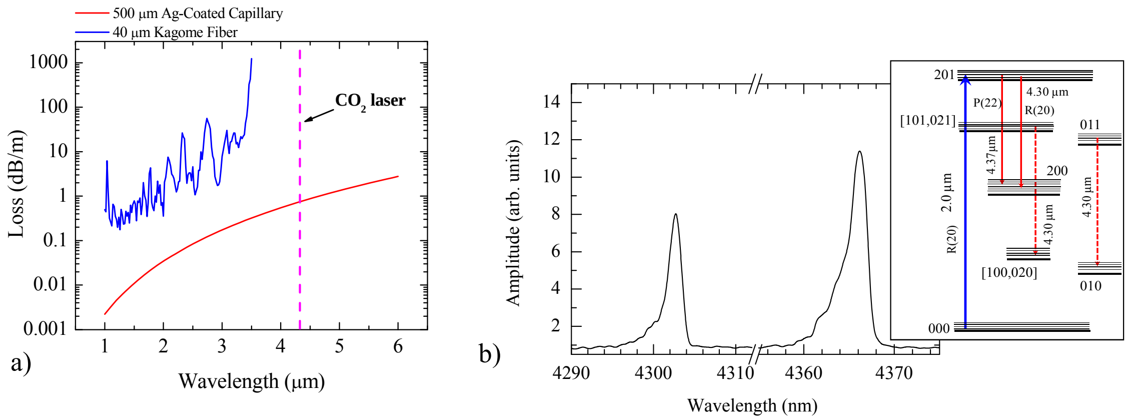

Fig. 3 a) Transmission of a 500 µm diameter silver coated hollow waveguide along with transmission of a traditional kagome silica HCF in the mid-IR region, and b) optically pumped CO_2 capillary laser showing emission in the 4.3 µm region. Inset shows the pump and lasing transitions in a vibrational energy level diagram of CO_2.

E.2. Towards a CW molecular iodine HOFGLAS

Molecular iodine, I_2, is an attractive molecule for optically pumped lasers because of its absorption and emission lines cover a broad spectrum from the VIS to the near IR [15, 16]. . We designed and theoretically analyzed an optical setup to demonstrate CW lasing. Figure 4 shows the layout of the laser and simulation results of the coupling efficiency of the laser mode after reflection off the curved end mirrors as a function of the mirror position.

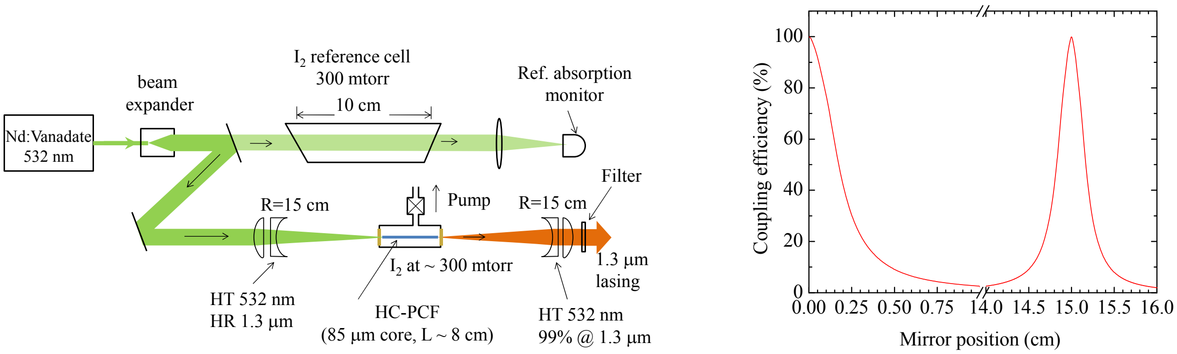

Fig. 4: left: Schematic diagram of a CW I_2 HOFGLAS system. Right: Calculated resonator coupling efficiency as a function of cavity mirror position.

The envisioned laser is pumped by the 2nd harmonic of a CW Nd:Vanadate laser tuned to the R53($v' = 32 \leftarrow v'' = 0$) absorption transition of I_2. The fluorescence in the 1.3 µm region emitted from the hollow core fiber (core diameter ~ 85 µm, pitch ~ 23 µm) was observed and is shown in Fig. 6.

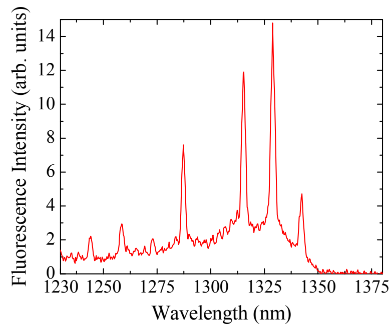

Fig. 5: Emission spectrum of the 532 nm pumped I_2 filled fiber.

Using a single frequency diode laser tunable around 1.3 µm, we also probed the double pass gain from the 8-cm hollow core fiber filled with 300 mTorr of I_2 and obtained about 35%.. This is very promising for a successful demonstration of a CW I_2 HOFGLAS.

E.3. Modeling results and capabilities

To evaluate scaling potentials and performance limits of optically pumped gas lasers, we developed computer based laser models that can take into account molecular kinetics in addition to the propagating pump and laser fields [18,19] in traditional laser systems with gas tubes. We undertook the first steps to modify the theory for HOFGLAS and to produce preliminary results that explain our observations; Fig. shows an example.

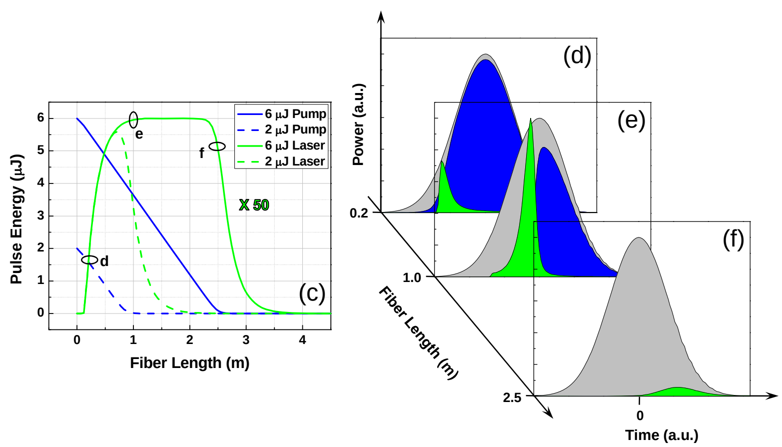

Fig. 6 Left: Calculated C_2H_2 laser energy as a function of fiber length for different pump energies showing the effect of pump saturation. Right: Evolution of the laser pulse (green) and pump pulse (blue) as they propagate through the fiber. The input pump pulse (grey) is also shown for comparison. Figure adapted from Ref. [7].

We have investigated the saturation of the laser output with absorbed pump power and predicted the insensitivity of laser output power to fiber length in a certain regime, which we have also observed experimentally [1]. For a better quantitative agreement of simulation and experiment a more comprehensive gas model is necessary, taking into account additional energy levels and relaxation processes. In addition the mode profile in the HCF must be considered.

E.4. Fiber design and fabrication: Low loss HCF for HOFGLAS

Since their first demonstration [17] two major families of HCFs have emerged. The first one is a photonic bandgap guiding HCF [18], and the second is an inhibited-coupling guiding HCF [12]. The photonic-bandgap guiding HCF has potential of guiding light with ultra-low transmission loss; however, it exhibits a limited optical bandwidth. Furthermore, the strong power overlap of the guided mode with the silica core-surround limited the optical power handling of this type of HCF.

On the other hand, the inhibited-coupling guiding HCF, which is coined kagome-like HCF, guides over much larger bandwidth but with higher transmission loss figures. The bandwidth and fiber loss can be tuned by the pitch and core shape of the fiber. Using this methodology, we have recently dramatically reduced the fiber loss to ~30 dB/km at 1550 nm by introducing the hypocycloid core shaped kagome HCF [19]. Finally, the guided mode of this fiber exhibits a much lower power overlap with the silica core-surround, making it an ideal host for high power gas lasers.

The transmission characteristics of different kagome fibers over our spectral range of interest are shown in Fig. 7. Two types of hypocycloid-core kagome HCF were investigated. The first one consists of 3-ring (Fig. 7, left panel) cladding and the second one of 1-ring cladding (Fig. , right side panels). For both, different pitches and strut thickness were investigated. The loss of the kagome fibers was characterized with cut-back measurements in the near-IR using a broadband illumination source and an optical spectrum analyzer to record transmission versus wavelength. For the 2.6 μm to 3.6 μm region, an optical parametric amplifier (OPA) was used as a probe.

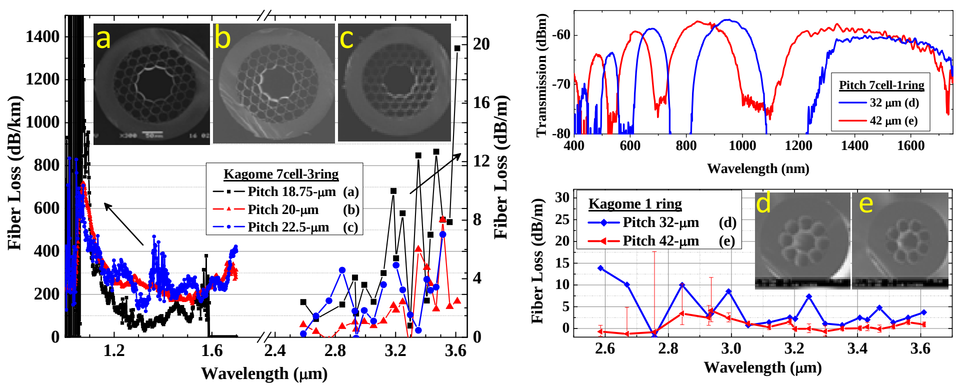

Fig. 7 (a-c): Kagome HCF having hypocycloid core with 3 cladding rings and 7 cell defects with pitches of 18.75 μm, 20 μm, and 22.5 μm and core diameters of 85-93.75, 87.5 – 92.5, and 85-93.75 μm; (d-e): kagome fibers with hypocycloid core structure having 1 cladding ring with pitches of 32 μm and 42 μm and core sizes of 58 μm and 64 μm respectively. (left) fiber loss versus wavelength in the near and mid-IR for 3 ring hypocycloid fibers (a)-(c). (Right top) Transmission of 1 ring kagome hypocycloid core fibers in the near-IR. For reference, the loss in the 42 μm pitch fiber (red) is measured to be 5 dB/m at 1.50 μm wavelength. (Right bottom) mid-IR loss of 1 ring kagome hypocycloid core fibers measured with the OPA. Error bars are generated from repeatability of two cut-backs of fiber length 0.8 and 2.0 m.

The fiber loss measurements were performed by measuring the ratio of input to output power as a function of wavelength (OPA tuning) for a single fiber length, and then cutting the fiber to a shorter length and repeating the ratio measurement. This was usually repeated so that two cut-back measurements were performed for each fiber. This process is lengthy and uncertainty arises due to its sensitivity to OPA power, mode and bandwidth while tuning. The error bars represent the repeatability of the measurement. The resulting curves represent the average of the fractional transmission through 1 m lengths based on two separate cutback measurements. For example, at 3.61 μm in the 42 μm pitch kagome 1-ring fiber (Fig. 7, right bottom), the upper limit of the loss is 1.45 dB/m, as indicated by the error bar.

Both types (3-ring and 1-ring) of fibers have extremely small loss in the 3-μm region while still maintaining acceptable loss (~ < 5dB/m, with a minimum reaching 30 dB/km) in potential pump wavelength regions at ~1.5 μm. The hypocycloid structure exhibits a larger wavelength region where losses are below 1.5 dB/m and its fiber properties can be tuned for particular target lasing and pump wavelengths, making this breed of hollow fibers ideal for HOFGLAS applications.

E.5. Coherent broadband mid-IR sources for spectral loss measurements

For many features of our work it is important to know the wavelength-dependent loss of the kagome fiber. A broadband source centered at 3 μm would be ideal for measuring this loss; however the lack of availability of such a source and high sensitivity mid-IR detectors make this measurement difficult, as indicated by the size of the error bars above. To satisfy this need, we are developing a modelocked Tm/Ho fiber laser to serve as a seed source to generate a supercontinuum to extend from 2 to 3 μm in a ZBLAN fiber. First, we demonstrated a self-starting, passively mode-locked Tm/Ho co-doped fiber laser that lases at one of two center wavelengths [20]. Mode-locking is obtained via nonlinear polarization rotation using a c-band polarization sensitive isolator with two polarization controllers and the laser produces 966 fs solitonic pulses because the net cavity dispersion is negative. The laser is able to pulse separately at either 1.97 μm or 2.04 μm by altering the intracavity polarization during the initiation of mode-locking. In order to produce shorter duration pulses, the net cavity dispersion must be made closer to zero in order for the laser to mode-lock in the stretched pulse regime. For intracavity dispersion an ultra-high numerical aperture (UHNA) fiber which exhibited normal group velocity dispersion was used in the cavity. This allowed the laser to mode-lock in the stretched-pulse regime producing 450 fs pulses [21]. Better control of higher order dispersion, specifically third-order dispersion, is necessary to produce even shorter pulses while operating in the stretched pulse regime. We are currently investigating the use of other UHNA fibers for both second and third order dispersion compensation in the cavity. The final step will be to inject the pulses into a ZBLAN fiber to produce the mid-IR supercontinuum.

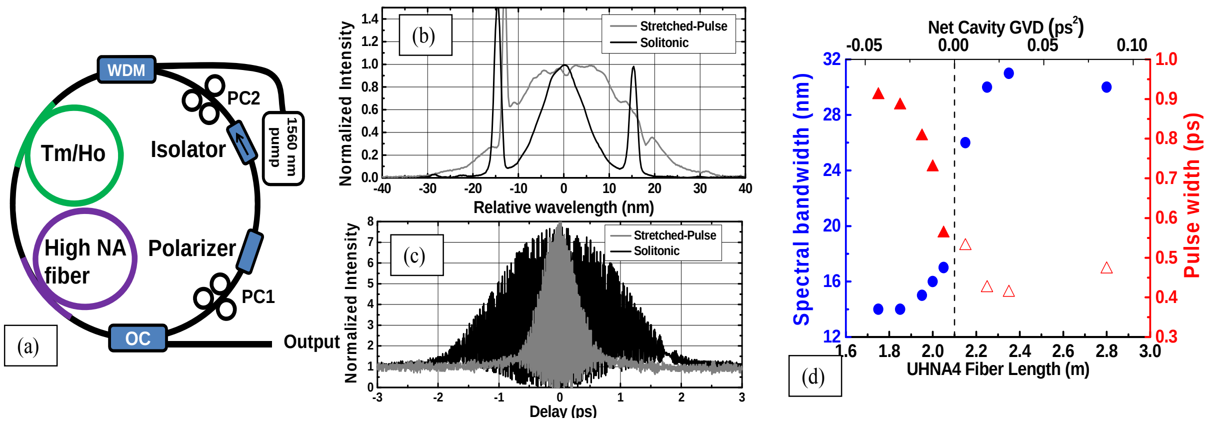

Fig. 8 (a): The mode-locked Tm/Ho fiber laser: WDM, wavelength division multiplexor; OC, output coupler; PC, polarization controller. (b) Output spectra of the laser in stretched-pulse (gray) and solitonic (black) operation for a UHNA fiber length of 2.35 m. The center wavelengths were 1960 nm and 1940 nm in solitonic and stretched-pulse regimes respectively. (c) The interferometric autocorrelation trace for stretched-pulse (gray) and solitonic (black) operation for a UHNA fiber length of 2.35 m. (d) Output spectral bandwidth (blue circles) and pulse widths (red triangles) for different lengths of UHNA fiber inside the cavity.

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